Fermi National Accelerator Laboratory

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PIP-II LB650 Cryomodule Technical Requirements Specification

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Document Approval

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Revision	Date of Release	Description of Change
-	6 Nov 2019	Initial Release
A	7 Nov 2019	Fixed links in document. Corrected reference ED number for PRD.
B		
C		

Table of Contents

1. Purpose

The Technical Requirements Specification (TRS) is intended to provide design parameters to scientists, engineers, and designers for delivering a technical design for the 650 MHz β=0.61 (LB650) cryomodule.

This specification addresses the design and technical details of the PIP-II LB650 cryomodule and its key components operations. It includes cryomodule physical size limitations, cryogenic system requirements and operating temperatures, alignment requirements, power coupler ratings, frequency tuner ranges, diagnostic instrumentations, and interfaces to interconnecting equipment and adjacent modules.

2. Scope

The technical requirements for low beta 650 MHz (LB650) cryomodule are based on the PIP-II Global Requirements Document (GRD), the Physics Requirements Documents (PRD), and the Functional Requirements Specification (FRS).

3. Acronyms

PDR	PIP-II Preliminary Design Report
GRD	Global Requirements Document
PRD	Physics Requirements Document
FRS	Functional Requirements Specification
EPDM	Engineering Process Document Management
FEM	Fermilab Engineering Manual
FESHM	Fermilab ES&H Manual
FRCM	Fermilab Radiological Control Manual
LB650	Low Beta 650 MHz
HB650	High Beta 650 MHz
CM	Cryomodule
PIP-II	Proton Improvement Plan II Project
SCD	System Configuration Document
TC	Teamcenter
UHV	Ultra-High Vacuum
MAWP	Maximum Allowable Working Pressure
MLI	Multi-Layer Insulation
LCLS	Linear Coherent Light Source
LLRF	Low Level Radio Frequency

SW	Standing Wave
TW	Travelling Wave
RF	Radio Frequency
FE	Final Element
FPC	Fundamental Power Coupler
VTS	Vertical Test Stand
HTS	Horizontal Test Stand

4. Reference

#	Reference	Document #
1	PIP-II Preliminary Design Report	PIP-II-doc-2261
2	PIP-II Global Requirements Document	ED0001222
3	PIP-II LB650 Cryomodule Functional Requirements Specification	ED0001830
4	PIP-II Cryogenic Heat Load Analysis	ED0008200
5	LB650 Cavity Design Choice Evaluation	ED0006943
6	PIP-II SRF Cavity Parameters PRD	ED0010221
7	LCLS-II Cryomodule SRF Cavity Tuner	LCLS II-4.5-ES-0385
8	Fermilab Environmental Safety and Health Manual (FESHM)	-
9	Fermilab Engineering Manual (FEM)	-
10	Fermilab Radiological Control Manual (FRCM)	-

5. LB650 Cryomodule Requirements

4.1 Introduction

The PIP-II LB650 cryomodule will operate with continuous wave (CW) RF power and support peak currents of 10 mA chopped with arbitrary patterns to yield an average beam current of 2 mA. The RF power per cavity at 2 mA average current and 11.9 MV accelerating voltage should not exceed 26.6 kW with all overheads [3]. Designs compatible with both CW and pulsed RF operation are encouraged to be examined, but not required.

The beam optics design for PIP-II requires that the 650 MHz, beta=0.61 cryomodule contains 4 identical cavities. There are no magnets or beam instrumentation elements inside the cryomodule.

The cavity string components consisting of the qualified dressed cavities, interconnecting beam tube sections, and beam vacuum valves will be specified, fabricated, procured, and prepared for assembly in a manner consistent with final cavity string assembly in a class 10 cleanroom. Strict adherence to the Superconducting RF components cleanroom protocols must be observed.

All external connections to the cryogenic, RF, and instrumentation systems are required to be removable junctions at the cryomodule. The only connection to the beamline shall be the beam pipe, which is to be terminated with “particle free” beam vacuum valves at both ends. Mean-Time-Between-Failure and Mean-Time-to-Repair are important design considerations for the cryomodule. Provisions for some maintenance operations must be provided, to make possible in-situ maintenance, namely without removing the cryomodule from its installed position.

Cavity alignment features shall be such that they can be translated to fiducials installed on the vacuum vessel. The same features on the cavities should be used to monitor cavity alignment after cooldown. Provisions must be provided on the cryomodule to monitor the cavity alignment without compromising vacuum or other performance requirements of the cyomodule or cavities.

Throughout this specification, 2 K refers to the sub-atmospheric, cavity side helium circuit, 5 K refers to the JT-valve side of the helium supply and low temperature thermal intercept circuit, and 50 K refers to the intermediate thermal shield and thermal intercept circuit, regardless of their actual operating temperatures

4.2 Cryogenic System Pressure Ratings

Anchoring and thermal contraction of each cryogenic circuit will consider worst case pressure, temperature and alignment extremes. All cryogenic circuits shall be designed to allow cool down or warm up independent of the state of other circuits. The LB650 cryomodule MAWP is listed in Table 2

Table 2 CRYOGENIC SYSTEM PRESSURE RATINGS

System	Warm MAWP (bar)	Cold MAWP (bar)
2 K, low pressure	2.05	4.10
2 K, positive pressure piping	20	20
5 K piping	20	20
35-50 K piping	20	20
Insulating vacuum	1 (external) vacuum inside	N/A
Cavity vacuum	2.05 (external) vacuum inside	4.10 (external) vacuum inside
Beam pipe outside cavities, includes beam position monitors and warm to cold transitions	1 (external) vacuum inside	1 (external) vacuum inside

4.3 Magnetic Shielding Requirements

The remnant magnetic field at the SRF cavity surface in the cryomodule shall be limited to avoid the significant increase in cavity residual resistance (Q_0 degradation) which occurs when magnetic flux is trapped as the cavity is cooled through the superconducting critical temperature (9.2 K). The magnetic shielding shall attenuate the Earth’s magnetic field, and the magnetic field generated by all surrounding components, both internal and external to the cryomodule, to preliminarily below 5 mG at the cavity surface. Final requirements on magnetic shielding attenuation will be set based on the results of a magnetic flux expulsion experiment of bare 650 MHz cavity at VTS.

To minimize remnant field, no magnetic (μ >1.1) components, such as flanges and bolts, may be used in the cryomodule. The magnetic shielding design shall consider penetrations and holes which are necessary for helium vessel cryogenic piping, mechanical supports, etc.

The as-built magnetic shielding shall be tested to ensure conformity to the specification, for each shielding assembly. Stainless steel components will need to be verified that they have not become magnetized during cutting or welding tasks. Transportation, assembly, and cooldown/warmup procedures shall be specified to ensure the magnetic shielding material is not subject to mechanical deformations or impact.

4.4 Cryomodule General Requirements

General requirements for the LB650 cryomodule are outlined in Table 1. Requirements of maximum allowed heat loads in the LB650 cryomodule are set according to the PIP-II Cryogenic Heat Load Analysis document [4]

Table 1 LB650 CRYOMODULE GENERAL REQUIREMENTS

Cryomodule	Parameter	Value
	Beam pipe aperture, mm	118
	Overall length (flange-to-flange), m	4.32
	Overall width, m	2.1
	Beamline height from the floor, m	1.3
	Cryomodule height (from floor), m	2.82
	Ceiling height in the tunnel, m	4.1
	Cryomodule weight, kg	<12000
	Maximum allowed heat load to 50 K, W	125
	Maximum allowed heat load to 5 K, W	25
	Maximum allowed heat load to 2 K, W	80
	Maximum number of lifetime thermal cycles	50
	50 K thermal shield temperature range, K	35-50
	5 K thermal intercept temperature range, K	5-15
	Cryo-system pressure stability at 2 K (RMS), mbar	~0.1
	Environmental contribution to the internal magnetic field at cavity surface, mG	<5*
	Beam duration for operation in pulsed regime, ms	≤1
	Repetition rate for operation in pulsed regime, Hz	≤20
Cavities	Parameter	Value
	Cavities number per cryomodule	4
	Frequency, MHz	650
	β geometric	0.61
	Nominal operating temperature, K	2
	Operating mode	CW
	Maximum Beam Current, mA	2
	Maximum dynamic cavity heat load to 2 K, W (each, including coupler)	20
	Coupler power rating (TW, full reflection), kW	35.0
	Longitudinal cavity alignment error, mm RMS	<0.5
	Transverse cavity alignment error, mm RMS	<0.5

	Angular cavity alignment error, mrad RMS	≤1

* Preliminary value, to be verified experimentally.

4.5 Cryomodule Interfaces

The cryomodule assembly has interfaces to the following:

- Bayonet connections for helium supply and return.
- Cryogenic valve control systems.
- Cryogenic system interface is via a heat exchanger which pre-cools helium from approximately 5 K to 2 K upstream of the cryomodule liquid level control valve (JT-valve).
- Pumping and pressure relief line connections.
- Cryomodule warm support structures.
- Beam tube connections terminated by a particle free vacuum valve.
- Input RF power connector
- Instrumentation connectors on the vacuum vessel shell.
- Alignment fiducials on the vacuum vessel shell with reference to cavity positions.

4.6 Cryomodule Instrumentation

Cavity and cryomodule instrumentation will include, but not be limited to the following:

- Cavity field probes.
- Coupler e-probes.
- Cavity tuner control and diagnostics.
- Input coupler temperature sensors.
- Thermal shield temperature sensors.
- Cavity helium vessel temperature sensors (externally mounted).
- Helium system pressure taps.
- Helium level probes in the 2 K phase separator.
- Helium temperature sensors in the 2 K phase separator.
- Cavity vacuum monitors.
- Insulating vacuum monitors.
- Internal magnetic field probes

Internal wiring shall be of a material and size that minimizes heat load to the internal systems.

4.7 Engineering and Safety Standards

All vacuum vessels, pressure vessels, and piping systems will be designed, documented, and tested in accordance with the appropriate Fermilab ES&H Manual (FESHM) chapters [8]. This includes the superconducting cavities and their associated helium vessels which must be designed, manufactured, and tested in accordance with FESHM chapter 5031.6, Dressed Niobium SRF Cavity Pressure Safety. Bellows shall be designed using the requirements of the Expansion Joint Manufacturers Association (EJMA). The cryomodule as a whole shall be designed to be free of frost and condensation when in operation in air with a dew point of 60 F. All cryomodule components design, production and testing shall comply to the Fermilab FEM procedure [9].

4.8 Quality Assurance

A complete cryomodule traveler is to be developed documenting all stages of materials inspection, cryomodule component fabrication, piping and weld inspection, cryomodule assembly, and test.

4.9 Technical References

For purposes of calculating pressure relief requirements, conduction and radiation heat loads, etc., the following assumptions shall be used:

- Worst-case heat flux to liquid helium temperature metal surfaces with loss of vacuum to air shall be assumed to be 4.0 W/cm^2.
- Worst-case heat flux to liquid helium temperature surfaces covered by at least 5 layers of multi-layer insulation (MLI) shall be assumed to be 0.6 W/cm^2.
- Thermal radiation to the 2 K or 5 K level under a 50 K thermal shield is approximately 0.1 W/m^2.
- Thermal radiation to the 50 K thermal shield from room temperature vacuum vessel is approximately 1 W/m^2.

6. LB650 Cavity Requirements

5.1 Introduction

The low beta 650 MHz 5-cell elliptical cavities will be designed, manufactured, processed, tested, and assembled into cryomodules for the PIP-II linac. This document covers the performance and test requirements for the LB650 cavity which consists of the following parts:

- Niobium superconducting cavity
- Liquid Helium containment vessel
- Active frequency-adjustment system
- High power RF coupler

The final cavity design shall be determined by a review process based on the criteria given in this section, and the performance of prototype cavities.

5.2 Electromagnetic Design

The 650 MHz 5-cell elliptical cavities with geometric velocity factors β_G = 0.61 have been selected to optimize acceleration efficiency. The cavities are required to operate in pulsed and CW modes in superfluid helium at a temperature 2.0 K, with nominal energy gain of 11.9 MeV at optimal beta and unloaded quality factors, $Q_0 > 2.3 \times 10^{10}$. The cell shape shall be designed to minimize the peak surface magnetic and electric fields, H_{peak} and E_{peak}, to minimize field emission and multipacting [5]. The cavity beam line aperture shall be optimized within the constraints on field stability, surface fields and RF load. The cavity design shall include end groups with ports for fundamental RF power coupler and pickup probe, and interface for frequency tuner.

5.3 Mechanical Design

The cavities are required to operate in CW RF mode in superfluid helium at a temperature of 2.0 K. Designs compatible with both CW and pulsed RF operation are encouraged to be examined, but not required.

The beam line aperture and cell shape shall be optimized to maintain mechanical stability and a high probability of effective surface processing. The cavity wall thickness and stiffening ring location shall be designed to satisfy FNAL engineering safety standards, acceptable response to microphonics, and Lorentz-force detuning, and overall tunability. The presence and type of fast and/or slow tuners shall be determined before the cavity design is considered complete. The cavity mechanical design shall be consistent with suitable mounting and alignment schemes for cryomodule assembly. The end groups shall incorporate a suitable interface between the cavity and its helium vessel as well as with tuner

In order to meet the requirements of the Fermilab ES&H Manual [8,9] several coupled thermal/structural analyses must be performed to assure a safe operation. These may include but should not be limited to the following: elastic, elastic-plastic, collapse, buckling and ratcheting. The cavity mechanical design shall be consistent with suitable mounting and alignment schemes for cryomodule assembly.

5.3 Helium Vessel Design

The Helium vessel shall be fabricated from titanium or equivalent non-magnetic metal, designed to house a 2 K helium bath sufficient to remove up to 33 W average dissipated power, with appropriately sized supply and return piping. It must meet the requirements of the Fermilab ES&H Manual for cryogenic pressure vessels and be rated at an MAWP of no less than 2.05 bar at room temperature and 4.10 bar at 2 K. Every effort should be made to minimize the weight and physical size of the helium vessel in all dimensions. The Helium vessel design has to support effective magnetic field repulsion in the course of fast cavity cooling

5.4 Tuning System

In order to accomplish the requirements for frequency range and resolution, the tuning systems for cavities of narrow bandwidths, such as LB650, typically integrate coarse and fine mechanisms engaged in series. The first normally utilizes a stepper motor with large stroke capability and limited resolution, the latter usually contains piezo-electric actuators with limited stroke but virtually infinite resolution.

The LB650 tuning system will be the same as for the HB650 cavity. The coarse tuner is predominantly used to achieve consistently the resonant frequency during cool-down operations and for preloading the piezo-electric actuator. The range necessary to compensate for the cool-down and detuning uncertainties is estimated to be ±75 kHz. If a cavity needs to be detuned as a result of a malfunction, the coarse tuning system must be able to shift the frequency away from resonance by at least 1000 bandwidths which equal to ≈ 64 kHz, so that the beam is not disturbed. For preloading of the piezo-electric actuator additional deformation of the cavity needed corresponding to 50 kHz frequency shift. The total coarse tuner frequency range is required to be 200 kHz. The minimal cavity frequency tuning sensitivity is at least 150 kHz/mm and, thus the coarse tuner shall be able to change cavity length by 1.3 mm.

The requirement on the resolution of the coarse tuning system was set to a value that would allow operation in the event of a failure of the fine-tuning system. Based on other applications, it is believed that such resolution can be achieved with a coarse tuning system.

It is conservatively assumed that the coarse system cannot be operated during beam acceleration; it is thought that the vibration of a stepper motor may induce vibrations in the cavity severe enough to disrupt the operation.

Fine tuners shall be designed to compensate the frequency shifts of the cavity induced by the Lorentz Force Detuning (LFD) and fluctuations of the helium bath pressure. The use of fine tuners is mandatory for pulsed operation and will reduce considerably the hysteresis of the system by limiting the elements in motion during the tracking of the frequency for pulsed and CW operations. An operation of the fine (piezo) tuners will be controlled by LLRF hardware. The control algorithm should prevent cavity detuning due to microphonics and the Lorentz Force Detuning. The latter is critical for cavity operation in the pulsed regime.

A particular design effort shall be dedicated to facilitate the access to all actuating devices of the tuning system from access ports on the vacuum vessel. All actuating devices must be replaceable from the ports, either individually or as a whole cartridge.

5.5 External Interfaces

The cavity shall interface to the cryomodule, the beam pipe, cavity supports, RF input and output coupler ports, and instrumentation feedthroughs. The cavities shall include fiducial features that will aid in alignment.

5.6 Operation and Testing

The cavity electromagnetic, mechanical and operational requirements are summarized in Table 3

Table 3 LB650 CAVITY TECHNICAL REQUIREMENTS

EM design	Parameter	Units	Value
	Frequency	MHz	650
	Iris aperture	mm	88
	Effective length $L_{eff} = 5\cdot(\beta_g \lambda/2)$	mm	703
	Geometrical/Optimal beta β_{gt}	-	0.61/0.65
	Optimal shunt impedance $(R/Q)_{opt}$	Ω	341
	Energy gain at optimal beta V_{opt}	MeV	11.9
	Surface RF electric field E_{peak}	MV/m	< 40
	Surface RF magnetic field B_{peak}	mT	< 80
Mechanical	Parameter		Value
	Sensitivity to LHe pressure fluctuations of dressed cavity	Hz/mbar	< 25
	Lorentz Force Detuning coefficient	$Hz/(MV/m)^2$	< 2.2
	Longitudinal stiffness	kN/mm	< 5
	Operating frequency tuning sensitivity	kHz/mm	> 150
	MAWP RT/2 K	bar	2.05 / 4.10
Operational	Parameter		Value
	Operating Field Flatness in dressed cavity	%	> 90
	Operating cavity gradient $G_{acc} = V_{opt}/L_{eff}$	MV/m	16.9
	Acceptance accelerating gradient in VTS	MV/m	> 20
	Operating temperature	K	2.0
	Unloaded quality factor Q_0	-	$> 2.3\cdot10^{10}$

	Acceptance quality factor Q_0 in VTS	-	$2.6 \cdot 10^{10}$
	Dynamic RF power dissipation	W	< 20
	Operating LHe Pressure	mbar	30±5r
	Max Leak Rate (room temp)	atm-cc/sec	< 2×10^{-10}
	Operating cavity Q-loaded/bandwidth	Hz	$1.04 \cdot 10^7$ / 62.5
	Operating input RF power CW	kW	≤ 26.6
	Operating field probe RF Power CW	mW	100 – 500
	Multipacting free zone at operating gradient	%	± 10
	Field emission free zone	MV/m	0—20
Frequency tuning	Parameter		Value
	Coarse frequency range	kHz	200
	Coarse frequency resolution	Hz	≤ 3
	Fine frequency range	Hz	1000
	Fine frequency resolution/stiction	Hz	≤ 0.5

5.7 Cavity Functional and Technical Specifications Compliance

Features and availability at several facilities shall be required to ensure compliance with the cavity functional specification.

Cavity Inspection

The cavities' manufacturing conformance will be determined upon arrival at Fermilab. Four incoming inspections are anticipated: An initial visual inspection to ensure overall quality of cavity and shipment integrity, CMM measurement to determine the cavity has been manufactured according to the drawings, a room-temperature leak check, and a room temperature RF measurement of field flatness, and fundamental pass band frequencies. Acceptance tolerances are: ± 3 mm for the cavity length and ± 0.5 MHz for the fundamental mode frequency.

Cavity Processing and Preparation

The cavity internal surface shall be prepared with a recipe which ensures with high probability that the Q_0, gradient and field emission levels will satisfy the requirements given in this document, with minimum cost and schedule impact. These cavities will receive bulk material removal by buffered chemical polishing in multiple steps, a hydrogen degasification bake in a vacuum oven, Nitrogen doping and inner surface cleaning via high pressure ultra-pure water rinsing. Upon completion of the surface preparation, the cavities will be assembled for testing and qualification in a cleanroom environment.

Cavity Test

The performance of the cavities will be measured in terms of three figures of merit: Q_0 measured at the cavity operating gradient, maximum operating gradient, and field emission level at the operating gradient. These measurements will be obtained through two types of tests: a vertical test of the bare cavity in the VTS, and a horizontal test of the dressed cavity using high CW power (comparable to what the cavity would see in a beam line) in the HTS.

The vertical test shall be used for initial qualification of the manufacturing and processing efficacy. Cavity performance shall reach at least 20% above the operational gradient and 20% above the operational Q_0 requirements to be considered qualified in the vertical test. Diagnostic instrumentation for quench location and field emission measurement shall be available for the vertical test. The cavity will need to be protected from mechanical deformation due to vacuum pressure differential.

The horizontal test shall be used as a test of the coupler, tuning system and dressed cavity assembly. Performance consistent with operational requirements shall be required for horizontal qualification of the cavity and peripherals. he horizontal test may be partially waived during the production stages of the project, if justified by consistent performance.

5.8 Quality Assurance

Cavity design shall be built to applicable FNAL engineering safety standards, and all cavity handling, processing and testing shall be performed according to applicable FNAL environmental safety and health requirements. All cavity and peripherals handling, processing and testing shall be subject to additional training and safety requirements specific to the relevant facilities

Electronic cavity travelers shall be developed documenting all stages of cavity fabrication, inspection, processing and tests. Each cavity will be identified individually by a serial number appearing on the cavity (e.g. on one of the cavity flanges). A document summarizing the location, status and test results of all cavities shall be publicly accessible and continuously updated

Following the acceptable performance of prototype cavities, all elements that will be utilized on the production cavities (e.g. helium vessel, tuning system) shall undergo design reviews prior to being released for fabrication. The PIP-II/SRF management team will convene an appropriate review committee consisting of experts.

7. LB650 Fundamental Power Coupler Requirements

6.1 Introduction

PIP-II employs two types of 650 MHz superconducting cavities, low beta (LB650) and high beta (HB650) elliptical five cells cavities accelerating an H- beam. The maximum power delivered by LB650 cavities to the beam is about 23.8 kW in the case of 2 mA beam current. Accounting additional power for microphonics and mismatching compensation (cavity coupling is fixed) this requires a 26.6 kW coupler [6].

The 650 MHz coupler is an integral component in the LB650 and HB650 dressed cavities. The cavities are expected to remain in service for many years, and hence they must be designed and fabricated to support future performance upgrades in a straightforward manner. The estimated power reflection is less than 25% for LB650 cavities operating near their maximum voltages, at the nominal loaded quality factors and on-crest beam acceleration. To assure operational reliability, with suitable overhead at 2 ma current, all LB650 couplers shall be tested at 35 kW input RF power with full reflection and arbitrary reflection phase.

We describe here the technical requirements of the LB650 fundamental power coupler to meet the PIP-II goals

6.2 Electro-Mechanical Design

A coupler is a unit which transfers RF power to a superconducting accelerating cavity located inside a cryomodule. It is attached to an input coupler port on the cavity at one end and connected to a rectangular waveguide at the other.

Materials known to become brittle at cryogenic temperatures shall not be used for coupler components that may see temperatures lower than -120 K during normal or accidental conditions. The coupler ceramic window shall have dielectric loss constant (tangent delta) less than 10^{-4} at room temperature, or equivalent.

The coupler vacuum part shall be designed to support assembly with the LB650 cavity in a clean room. The material used for construction of the cold part of the coupler shall meet UHV, cryogenic and clean room requirements. The air part of the coupler will be installed from outside the cryomodule during final assembly. The ceramic window shall be equipped with a heater for preventing ice formation during coupler off-load and low power operations.

6.3 Operation and Testing

The LB650 FPC operational and test technical requirements are summarized in Table 4.

Table 4 LB650 FUNDAMENTAL POWER COUPLER REQUIREMENTS

Electromagnetic	Parameter	Value
	Frequency, MHz	650
	Pass band (S_{11}<0.1), MHz	> 2
	Maximum operating power, kW (CW, <25% reflection)	26.6
	Acceptance Testing power, kW (CW, any reflection)	35
	Loaded Q	1.04E+7 ± 20%
	HV bias, kV	± 4
	Ceramic window dielectric loss constant	<1E-4
Mechanical	Parameter	Value
	Input waveguide	WR-1150
	Output coaxial line aperture, mm	72.9
	Output coaxial line impedance, Ω	105
	RF window	Single, RT
	Cavity flange relative displacement, mm	± 3
	Vibration and shock, g (in any direction)	≤ 3
	Antenna tip centering, mm	< ± 1.5
	Antenna tip vibration (by air cooling), mm	< ± 0.1
	Vacuum leak tightness, l*Torr/s	< 2E-10
Thermal		
	Thermal intercepts (nominal), K	5 and 50
	Temperature at 5 K intercept, K	< 15
	Temperature at 50 K intercept, K	< 125
	Maximum 2K heat load, W	< 0.5
	Maximum 5K heat load, W	< 1.4
	Maximum 35-50K heat load, W	< 3.5
	Maximum antenna tip temperature, K	< 330
	Antenna cooling media	Air

	Air flow rate, g/s	< 3
	Max cooling air pressure drop, bar	< 1.5
	Air output temperature, K	< 320
Diagnostics		
	Temperature sensors (per each coupler)	7
	E-probe current monitor	1
	Bias current monitor	1
	Bias voltage monitor	1
	Air output flow monitor	1

6.3 External Interfaces

The LB650 power coupler has interfaces to the following:

- RF input port on the cavities.
- Connections to the 5 K, 35-50 K, and 300 K intercepts.
- E-probe connector.
- Heater connector.
- Cryomodule flange.
- RF input flange.
- Air inlet.
- Air outlet.
- HV bias connector.

6.4 Quality Assurance

All designs shall be built to applicable FNAL engineering safety standards, and all coupler handling, processing and testing shall be performed according to applicable FNAL ES&H requirements. All coupler and peripherals handling, processing, and testing shall be subject to additional training and safety requirements specific to the relevant facilities

Electronic coupler travelers shall be developed documenting all stages of couplers incoming inspection, processing and tests. Each coupler warm and cold parts shall be identified individually by a serial number appearing on the coupler flanges. A document summarizing the location, status and test results of all couplers shall be publicly accessible and continuously updated.

8. LB650 Fundamental Frequency Tuner Requirements

7.1 Introduction

As described in the FRS for 650 MHz cryomodules, each SRF cavity will have an electromechanical frequency tuner. The 650 MHz SRF cavity tuner must be design in the way that can be used for both LB650 and HB650 cavities. To accommodate these requirements interfaces of LHe Vessel /Tuner and Cavity/Tuner need to be similar design. The design of the 650 MHz cold tuning system will incorporate technical solutions developed for the LCLS-II 1.3 GHz tuner system with appropriate scaling to fit to the 650 MHz cavity dimensions [7]

Outlined specifications defines the technical design and fabrication requirements for the Tuner Package. The Tuner Package contains both slow and fast tuning capabilities. The tuner is mounted on the upstream end of a cavity and operates in cold vacuum.

The tuners for 650 MHz low beta and high beta cavities will be designed, prototyped, tested, manufactured, assembled into dressed cavities, HTS tested and integrated with cavity controls in the cryomodule for PIP-II project. This document covers the performance and technical requirements for LB650 cavity tuner and its interface to LLRF system.

7.2 Mechanical Design

Main tasks of the superconducting RF cavity tuner are to tune the cavity to the desired resonance frequency by compressing the cavity and to compensate cavity detuning due to Lorentz-force detuning (LFD) and microphonics. Tuner requires both slow and fast tuning options for compensating static errors and dynamic loadings, respectively. The design of tuning mechanism needs to be carried out based on the electromagnetic requirement of the 650 MHz elliptical cavity. Figure 2 shows the cavity profile change before and after tuning in the schematic.

The kinematics model and the 3-D model of the tuner are shown in Figure 3. The coarse tuner is a double lever tuner (with a 20:1 ratio), that utilizes an electromechanical actuator to translate the rotation of the stepper motor to linear motion. The tuner works in the "cavity-push" direction by compressing the cavity. The fine tuner consists of a two piezo-stack that is installed between the coarse tuner's levers (top and bottom), close to the cavity end flange. Safety rods are placed between the cavity end flange and the main lever of the tuner to protect the cavity from non-elastic deformation during the cavity/helium vessel system leak check. The tuner is anchored to the helium vessel with two strong horizontal arms. These arms have adjustment capabilities to accommodate differences of up to several millimeters in the length of the 5-cell elliptical cavities after final tuning. Set-screws, special washers and lock-tight shall be used to prevent loosening of the assembly screws during warmup and cool-down cycles.

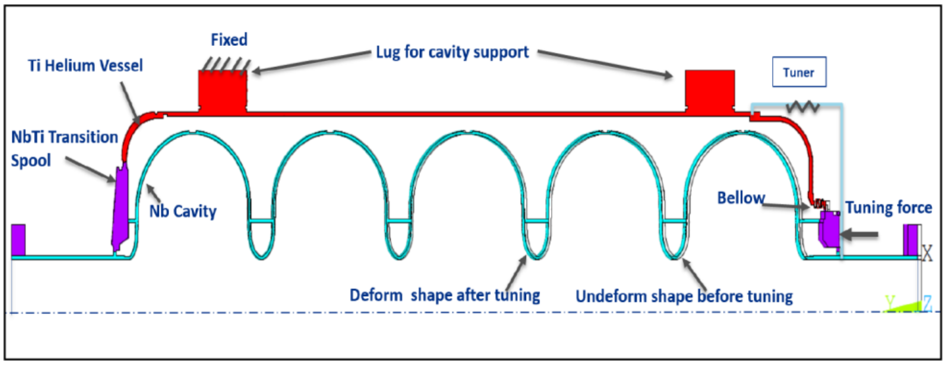

Figure 2 Schematic of cavity tuning for LB 650 MHz cavity.

A geared stepper motor with shaft system to translate rotation into linear motion will be used to drive the slow tuner. The development of appropriate slow tuning driver system is required as a part of tuner development. Each piezo-actuator will be driven by an amplifier capable to operate at a high capacitive load of the piezo-actuator. The amplifier voltage will be controlled by LLRF system.

For preventing the build-up of shearing forces on the piezo-stack during tuner operation the ball connections shall be used for the connections between the top and bottom encapsulated piezo stack and the main lever. Two adjustment screws, one in each main arm, will be used to uniformly preload the piezo-stacks during assembly. The tuner shall be equipped with two limit switches to limit the maximum range of the tuner arm motion.

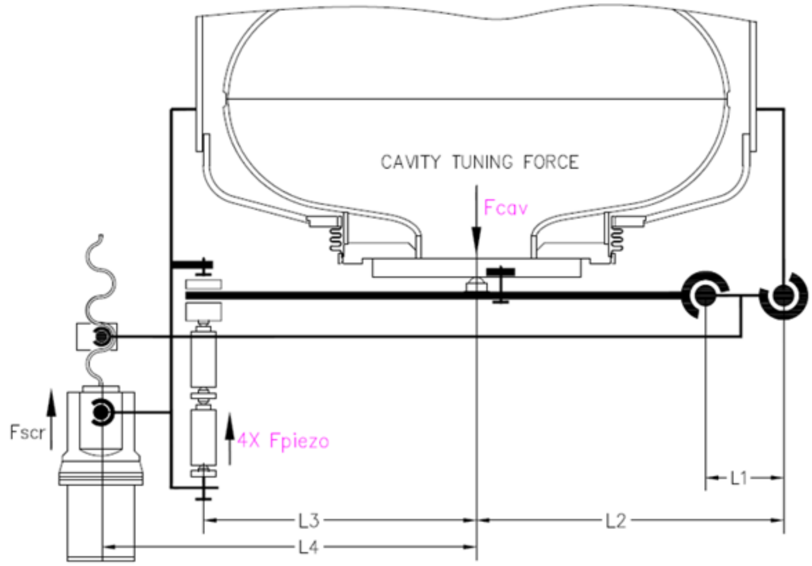

Figure 3 Scheme of a LB650 tuner kinematic model

To mitigate the risk of active tuner component failures, the tuner shall be designed so that the electromechanical actuator and piezo-stack are accessible and replaceable through special ports in the cryomodule vacuum vessel.

Cavities have manufacturing variances and they may be shortened or lengthened (inelastic tuning) at different stages of fabrication. The changes in dimensions (especially flange-to-flange length) may cause interface and assembly issues. A fine-adjustment system should be integrated to compensate for these variances.

Remnant magnetic fields produced by tuner components may affect cavity performance. All tuner parts shall be fabricated from non-magnetic or low-magnetic material, such as titanium or 316LN stainless steel. If for machining of the tuner's parts stainless steel 316L will be selected it must follow the heat treatments of the parts after all forming, cutting or welding operations are complete (1,000 °C for 1 hour). Residual magnetic field should be below specifications.

Cavities are handled in clean-room environment. Tuner parts should be designed and manufactured so that they are easy to clean. In those instances where this is not possible, sub-groups should be easy to remove and re-install to allow thorough cleaning.

The tuning system and its components will be installed and uninstalled frequently, especially on the first prototype. Design must be robust in this aspect. Weak links such as wires, small fasteners and all other delicate parts shall be resistant to normal handling.

The actual spring constant of the device could be different from the estimations due to the uncertainties in stiffness of contact regions, complex joints and bearings. FE Analyses should be performed, and small prototypes tested to verify the accuracy of predictions.

7.3 Tuner Lifetime

Reliable operation of the is an important factor in overall machine beam-time availability. The electromechanical actuator lifetime estimation is based on the XFEL/LCLS II scenario of linac operation: two warm-up /cool down cycles of the whole machine twice each year, and short-range tuning once a day, which is equivalent to 25 years of service for PIP-II cryomodules. The estimated operational requirement for the electromechanical actuator during the LB650 cryomodule lifetime is 1,250 spindle rotations.

The piezo-electrical actuator operational lifetime requirements for the LB650 cryomodule are estimated based on the following assumption for piezo operation:

- To compensate for the cavity resonance slow detuning caused by LHe pressure fluctuation, a stimulus pulse with $f_{modulation}$ ~ 0.01 Hz and V_{pp} < 50 V will drive the piezo all the time (<$8x10^6$ pulses for 25 years of operation).
- To compensate for the dynamic LFD of the SRF cavity, a stimulus pulse train of the ~10 pulses with $f_{modulation}$ ~ 200 Hz and V_{pp} < 100 V will drive piezo 5 time a second (<$4x10^{10}$ pulses for 25 years of operation)

Major concerns are radiation damage of the tuner active components: the piezo-electrical stacks and the electromechanical actuator. The actuator and piezo-stack shall withstand radiation dose up to level ~$5*10^9$ Rad over the tuner lifecycle.

7.4 Operational and Test Requirements

The LB650 frequency tuning system operational and test technical requirements are summarized in Table 6. The performance of the tuners will be required to measure in terms of their range, resolution and hysteresis for both the slow and fast tuners. Validation of tuner parameters to be done first on a prototype tuning mechanism. Based on the feedback of the prototype testing the tuner design need to be finalized.

Table 6 TECHNICAL REQUIREMENTS FOR THE LB650 TUNING SYSTEM

Mechanical	Parameter	Value
	Tuner-dressed cavity system stiffness, kN/mm	> 40
	Maximum force on the tuner system, kN	3.3
	Tuner operating temperature (insulating vacuum), K	10-60
Slow Tuner	Parameter	Value
	Slow tuner frequency range, kHz	200
	Stepper motor resolution, Hz/step	<2
	Slow tuner hysteresis, Hz	≤ 100
	Slow tuner dimensional range, mm	1
	Maximum force on the spindle system, N	165
	Stepper motor maximum operation current, A	2.5
Fast Tuner	Parameter	Value
	Piezo tuner frequency range, Hz	1200
	Piezo tuner frequency resolution, Hz	<0.5
	Piezo tuner dimensional range, µm	10
	Maximum operating force (each piezo capsule), N	800
	Piezo actuator maximum operating voltage, V	120
Lifetime	Parameter	Value
	Tuner operation lifetime, year	25
	Maximum number of electromechanical actuator spindle rotations	1250

	Maximum number of piezo-electrical actuator control pulses	4E10
	Maximum allowable radiation doze, Rad	5E9

* Experimentally measured values

7.5 Quality Assurance

The tuner quality shall be verified by:

- Materials control
  - Material properties shall be confirmed by supplier Material Certificate
- Mechanical parts quality control
  - Parts for tuner assembly must go through inspection to check
    - Tolerance on mechanical parts
    - Permeability of the parts
    - Absence of the grease on the bearing
- Electrical components quality control
  - Electromechanical actuator
    - Test of the actuator will be conducted at the factory at liquid N_2 temperature. Motor must be run at room temperature and at liquid N_2 temperature for a particular amount of the steps. The company must deliver QC protocol with: starting current under the load; total number of steps; lost steps.
    - Electromechanical actuator must be delivered in a seal bag including desiccant and humidity indicator
    - Electromechanical actuator wires shall be terminated on the factory on the specialized connectors per project specifications.
  - Encapsulated piezo-actuator
    - Four wires from two piezo-stack inside capsule shall be terminated on the factory on the specialized connectors per project specifications.
    - Quality control tests of the piezo-actuators must be done at the factory:
      - Piezo stroke vs applied voltage test for each unit
      - Burn-in tests of each units:
        - DC test: 100% of nominal voltage for 2 hours
        - AC test: nominal voltage amplitude sinewave of 100 Hz- for 3 min
- Fabrication documentation (drawings, travelers, inspection, discrepancy reports)

Any deviation from the specified or expected performance, and reference parameters should be verified, and approved before the tuner is accepted.

The details of each joint in the mechanism shall be carefully evaluated and measures taken to mitigate phenomena such as stick-slip, play, backlash that would increase the hysteresis. The system shall be tested prior to installation on the cavity. Aspects to be considered are: self-consistent sub-assemblies, ease of assembly and alignment, ease of transportation, protection features. Tests on critical components of the tuning system shall be performed to identify possible issues with reliability and life expectancy. After the tuning system is mounted with the cavity and the LHe vessel and before installation in the cryomodule, pressure test shall be performed for quality assurance and FESHM compliance.

9. Safety Requirements

The system shall abide by all Fermilab ES&H (FESHM) and all Fermilab Radiological Control Manual (FRCM) requirements including but not limited to:

Pressure and Cryogenic Safety
• FESHM Chapter 5031 Pressure Vessels
• FESHM Chapter 5031.1 Piping Systems
• FESHM Chapter 5031.5 Low Pressure Vessels and Fluid Containment
• FESHM Chapter 5031.6 Dressed Niobium SRF Cavity Pressure Safety
• FESHM Chapter 5032 Cryogenic System Review
• FESHM Chapter 5033 Vacuum Vessel Safety
Electrical Safety
• FESHM Chapter 9110 Electrical Utilization Equipment Safety
• FESHM Chapter 9160 Low Voltage, High Current Power Distribution Systems
• FESHM Chapter 9190 Grounding Requirements for Electrical Distribution and Utilization Equipment
Radiation Safety
• FRCM Chapter 8 ALARA Management of Accelerator Radiation Shielding
• FRCM Chapter 10 Radiation Safety Interlock Systems
• FRCM Chapter 11 Environmental Radiation Monitoring and Control
General Safety
• FESHM Chapter 2000 Planning for Safe Operations

Any changes in the applicability or adherence to these standards and requirements require the approval and authorization of the PIP-II Technical Director or designee.

In addition, the following codes and standards in their latest edition shall be applied to the engineering, design, fabrication, assembly and tests of the given system:

ASME B31.3 Process Piping
ASME Boiler and Pressure Vessel Code (BPVC)
CGA S-1.3 Pressure Relief Standards
NFPA 70 – National Electrical Code
IEC Standards for Electrical Components

In cases where International Codes and Standards are used the system shall follow FESHM Chapter 2110 Ensuring Equivalent Safety Performance when Using International Codes and Standards and requires the approval and authorization of the PIP-II Technical Director or designee.

Additional Safety Requirements that are not listed in the general list above shall be included in the Requirements table in the Functional Requirements section.